Noise Reduction Methods for Weighing Lysimeters

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Abstract: Mechanical vibration of the grass and crop weighing lysimeters, located at the University of California West Side Field Research and Extension Station at Five Points, Calif. generated noise in lysimeter mass measurements and reduced the quality of evapotranspiration (ET) data. The estimated power spectral density (PSD) for grass lysimeter mass data acquired at 1.3 ms intervals contained a large peak at 11 Hz. Crop lysimeter data produced similar peaks at frequencies greater than 1 Hz. An effective method for eliminating this noise source is arithmetic averaging of the data, which should be acquired sufficiently rapidly to avoid aliasing. The PSD also increased with decreasing frequency in the range 1.0–0.1 Hz. This noise was addressed by Savitsky–Golay (SG) filtering using 7-, 11-, and 15-point filters. Each filter was applied to the same data set consisting of 2,560 measurements taken during a 1-min interval every 10 min over a 26.3-h period. Noise reduction factors, defined as the ratio of standard deviation of filtered lysimeter mass to standard deviation of unfiltered mean values of lysimeter mass for subsequences of the same data, were 0.90, 0.88, and 0.86 for the 7-, 11-, and 15-point filters, respectively. For the daytime data only, the factors were 0.88, 0.85, and 0.83. The SG filters were more effective during daytime when most of the lysimeter ET occurs. These methods are simple enough to be programmed into commercially available dataloggers for real time filtering. Hourly averages of the standard deviations of lysimeter mass measurements bear a distinct nonlinear relationship to hourly mean wind speed confirming earlier suppositions that wind loading causes noise in counterbalanced weighing lysimeters.

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Introduction

Accurate irrigation scheduling is increasingly important due to economic factors and scarcity of water resources in many parts of the world (Molden and Oweis 2007). To address the needs of agricultural producers, models of evapotranspiration (ET) from crops have been developed to enable simple calculation of crop water requirements (Pruitt and Doorenbos 1977; Allen et al. 1989, 1998). Such models require estimation of reference-surface evapotranspiration (ET) rate and the development of crop coefficients that enable estimation of ET rates for specific crops (Pereira et al. 1996). The original FAO-24 model formulated the crop ET rate, under well-watered conditions, as simply the product of a crop coefficient and a reference ET rate (Pruitt and Doorenbos 1977). The updated version changed this formulation to provide separate coefficients for basal transpiration rate and soil evaporation (Allen et al. 1998; Ayars and Hutmacher 1994; Wright 1982). For either formulation, local estimates of reference ET rates are needed to provide producers with representative numbers for local weather conditions.

Measurement techniques for the determination of ET rate include Bowen ratio energy balance (BREB), eddy covariance (EC), and weighing lysimeters. The BREB method is based on estimation of the ratio ($\beta = \lambda E/H$) of latent heat flux (λE) to sensible heat flux (H) and the solution of an equation for energy flux balance at the earth's surface (Monteith and Unsworth 1990). The BREB calculation of latent heat flux was found to exceed lysimeter measurements of latent heat flux by 5.5% on average under advective conditions (Gavilán and Berengena 2007). The EC method provides direct measurements of the vertical fluxes of carbon dioxide and water vapor in the atmosphere but has some restrictions, notably adequate fetch and turbulent conditions (Baldocchi 2003). Of the various methods, weighing lysimeters provide the most accurate ET rates for a small surface area, whereas the BREB and EC methods provide a mean ET for a larger area representing the fetch of the instrument.

A weighing lysimeter measures the mass of soil and plants contained within it. Neglecting the change in mass due to plant growth, the difference of sequential mass measurements divided by the product of elapsed time and effective lysimeter area approximates the ET rate. This technical note concerns the diagnosis and amelioration of a vibration problem that has increased uncertainty in mass measurements of some weighing lysimeters. Specifically, the writers have studied weighing lysimeters that include a scale with a leverage system and a counterbalance weight that are operated using a small capacity load cell (Brown et al. 2001; Howell et al. 1985; Pruitt and Angus 1960). The vibrations discussed here are likely caused by wind, as has been noted in previous studies (Young et al. 1996; Howell et al. 1995). Limitation

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in the resolution of weighing lysimeters was a significant issue at other locations, for example, the frequency of comparisons of weighing lysimeter ET to BREB data was reduced from a 20-min period to 1 h due to limited precision of lysimeter ET (Gavilán and Berengena 2007). The main objectives of the study are quantification of the magnitude and frequency dependence of the lysimeter vibration, development of numerical methods to reduce noise in the evapotranspiration rate data, and analysis of the effectiveness of these methods. A secondary objective is characterization of the relationship between wind speed and lysimeter vibration.

Methods

Lysimeter Description and Operation

ET rates for grass and crops were measured using two weighing lysimeters located at the University of California West Side Research and Extension Center in Five Points, Calif. Each lysimeter consists of a steel housing containing a truck scale with a $2 \times 2 \times 2$-m soil box resting on it (Model FS-4, Cardinal Scale Manufacturing, Webb City, Mo.) These lysimeters were constructed in 2001 following removal of two earlier lysimeters located on the same site (Howell et al. 1985). Data collected to compute ET rates for both the grass and crop lysimeter are mass of the soil box and drainage water volume.

Tall fescue grass (Festuca arundinacea) was grown on the surface of the soil box in the grass lysimeter and on the surrounding 2.0-ha plot. The grass surface was flush with the surrounding plot and both were mown on a seasonally variable schedule to maintain a height of 0.1 m. The distance from the lysimeter to the edge of the grass field in the prevailing wind direction was 76 m. Irrigation of the lysimeter by subsurface drip occurred at various times during the day in order to restore the actual water loss that occurred (Phene et al. 1985). A tank for storing irrigation water was mounted on the weighing platform underneath the lysimeter soil box (Phene et al. 1991). When necessary the irrigation tank was refilled at night between 12:05 and 12:25 a.m. Pacific standard time.

During the winter and spring of 2007, drainage from the grass lysimeter was common. The drainage water was directed to a tipping-bucket rain gauge and hourly drainage volumes were recorded. Corrections of ET rate for drainage were done in postprocessing subsequent to downloading from the datalogger. ET rates obtained at the crop lysimeter for various crops were used to calculate crop coefficients (Wright 1982). In 2007 and January 2008 both the crop lysimeter and surrounding field had a bare soil surface. Thus the term, crop lysimeter, is considered a naming convention because the lysimeter was not cropped continuously. Other features of the crop lysimeter are similar to those described for the grass lysimeter.

A California Irrigation Management Information System (CIMIS) weather station (No. 2) is located a few meters from the grass lysimeter. These weather stations provide meteorological data for prediction of grass reference ET (Temesgen et al. 2005). A complete description of the weather station and the methods used to calculate grass reference ET can be found on the CIMIS web site (http://wwwcimis.water.ca.gov). The current work has made use of the wind speed recorded by a three-cup anemometer (Met-One, Model 014A, Met One Instruments, Inc., Grants Pass, OR) installed 2 m above the grass surface. Reported wind speeds are mean values for the previous hour.

Lysimeter Datalogging and Filtering Computer Programs

The original datalogger installed in both lysimeters was a model 21X [Campbell Scientific Inc. (CSI), Logan, Utah]. This datalogger had been programmed to take 300 load-cell measurements on-the-hour within approximately 1 min. The mean and standard deviation (SD) of the measurements were calculated. Noise reduction was achieved by a filter—included in the datalogging program—that eliminated data points having a magnitude of deviation greater than 1 SD. The mean of remaining data points represented lysimeter mass. In October, 2006 the 21X dataloggers were replaced by Model CR3000 (CSI). The load cells were also replaced by Omegadyne model LC101-100 and calibration factors obtained by placing known weights on the surfaces of the crop and grass lysimeters were 242.6 and 244.7 kg/mV, respectively. Subsequent to these changes, special data acquisition programs were entered into the dataloggers to provide collection of load cell output voltage every 1.3 ms for evaluation of the vibration problem.

Savitsky–Golay Filters

Calculation of first and higher order derivatives for uniformly spaced data can be performed by Savitsky–Golay (SG) methods (Press et al. 1996, Sec. 14-8). These methods are based on a weighted least-squares algorithm that provides estimates of the function value or its derivatives at the central point of a sequence of measurements. For example, a seven-point SG filter can provide an estimate of the derivative at the fourth point. This derivative was divided by lysimeter area to obtain the ET rate. In normal lysimeter operation the function value, lysimeter mass, was collected every 10 min starting at 5 min past each hour. Thus, the seven-point SG filter operated over a time period of 60 min. At 35 min past the hour the filtered hourly ET rates for 5 min before and 5 min after the hour were averaged to calculate the rate on the hour. Both 11- and 15-point SG filters were also tested. Weighting coefficients for all filters were calculated using the savgol subroutine (Press et al. 1996, Sec. 14-8).

Evaluation of SG Filters of Varying Lengths

Assessment of the performance of the three SG filtering methods was conducted by applying each filter to the 24-h filter assessment data set collected in January 2008 when the lysimeter surface was bare soil. These calculations simulated the normal datalogging operations described earlier, but were done by separate programs after the data were collected. Statistics for assessing effectiveness of the filters were calculated for lysimeter mass rather than ET rate. The filter assessment data set consisted of a 2,560-point sequence collected during a 1-min interval every 10 min over a 26.3-h period starting at 10:55 p.m., January 25, 2008. This period provided extra values to initiate and terminate a 15-point SG filter that would provide filtered lysimeter mass starting at 12:05 a.m. on January 26, 2008 and ending at 11:55 p.m. The data collected on January 26 are typical for clear days at this time of year.

The mean and median of the unfiltered data were calculated for each of ten 256-point subsequences. Successive mean and median values, taken every 10 min, were grouped in time series whose length was defined as the length of a particular SG filter. For example, the mean of the first 256 points taken at time t was placed in a time series followed by the mean of the first 256

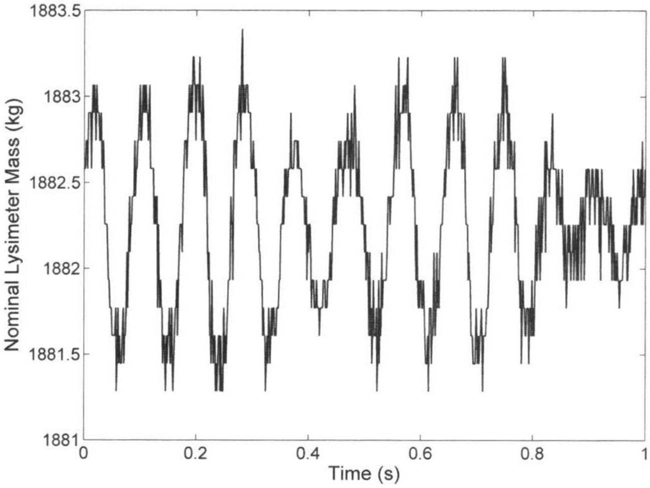

Fig. 1. Grass lysimeter nominal mass (kg) versus time

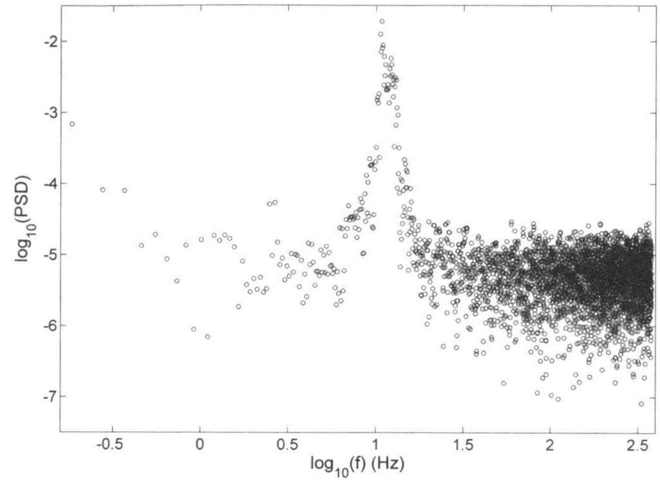

Fig. 2. Estimated PSD for grass lysimeter mass (kg) recorded during 10.8 seconds (8,192 points)

points taken at time $t+10$ min. Likewise, a time series was constructed for successive mean values from the second 256-point subsequence and so on. When each time series had accumulated to the length specified for a particular SG filter, the filter was applied, generating a filtered lysimeter mass for the central point of the time series.

Noise in the filtered data at time t was quantified by taking the standard deviation of the ten filtered lysimeter mass values. For the unfiltered data, ten mean values were calculated for the 256-point subsequences. Noise reduction factors were defined as the ratio of standard deviation of the ten filtered mass estimates to that of the ten mean values for unfiltered data.

Results and Discussion

Lysimeter Mass Variability

The mean and standard deviation of filtered ET rate for the crop lysimeter were 0.27 and 0.07 mm $\mathrm{h^{-1}}$, respectively, at midday on January 7, 2008 and would likely be greater in the summertime when ET rates approach 1 mm $\mathrm{h^{-1}}$. A range of reported lysimeter precision in millimeters of water is 0.02–0.1 (Pruitt and Angus 1960; Holmes 1984; Kirkham et al. 1991; Phene et al. 1991; Howell et al. 1995; Young et al. 1996; Brown et al. 2001). Thus, for the crop lysimeter, 1 SD of ET rate was in the upper portion of the range of reported lysimeter precision suggesting that some modifications of hardware or software could improve data quality. Installation of new load cells in October 2006 reduced the noise amplitude but the problem was not eliminated, which led to filtering the signal to improve the precision of these lysimeters.

Wind loading can induce vibration in lysimeters causing a loss of precision that may exceed 0.02 mm (Howell et al. 1985). The vibration spectrum for the grass lysimeter's load measuring system was evaluated by acquiring load cell output voltage at a sampling interval of 1.3 ms. Vibration caused temporal variations of the measured mass (Fig. 1). The power spectral density (PSD) of a uniformly sampled signal represents the power carried by the signal per unit frequency. Peaks in the PSD of a mechanical system are generated by resonances of the system. The estimated PSD for lysimeter mass using the same data set as represented by Fig. 1 contains a main peak near 11 Hz due to mechanical resonance in the load measuring system (Fig. 2). A similar plot for the crop lysimeter contained multiple resonance peaks at frequencies exceeding 1 Hz.

The estimated PSD for 1,280 data points collected during a 2-min sampling period from the crop lysimeter on January 14, 2008 at 12:05 p.m. indicates that vibration also tends to increase with decreasing frequency in the range 0.1–1 Hz and remains higher for frequencies in the range 0.01–0.1 Hz (Fig. 3). The PSD for the grass lysimeter also increases with decreasing frequency below 1 Hz (data not shown). These observations indicate that substantial vibration is occurring in these lysimeters at frequencies in the range 0.01–0.1 Hz. Considering that actual lysimeter mass changes by as much as 0.07 kg/min at midday in summer, the measurements taken during normal operations, requiring at least 1 min to complete, may include both actual mass changes and vibrational components. The standard deviation for five 256-point subsequences of the 1,280-point data set represented in Fig. 3 is 0.06 kg or about the same order as the maximum actual mass changes during one minute.

With respect to noise, two distinct issues are raised by these vibrational spectra. First, the noise represented by the large peaks in the PSD occurring at frequencies greater than 1 Hz can be

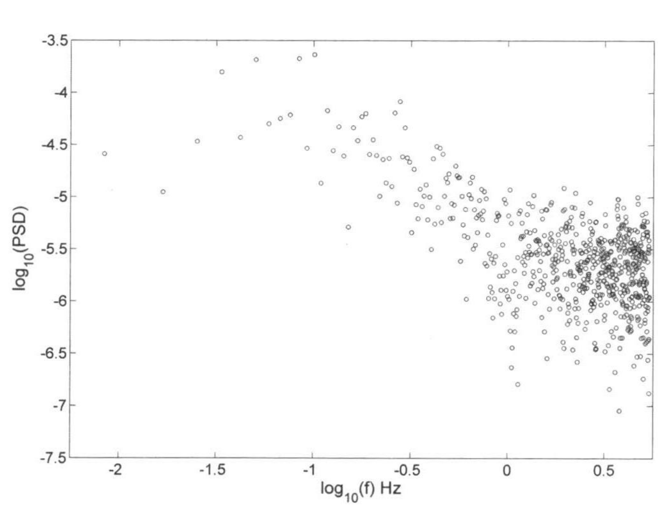

Fig. 3. Estimated PSD for crop lysimeter mass (kg) (1,280 points)

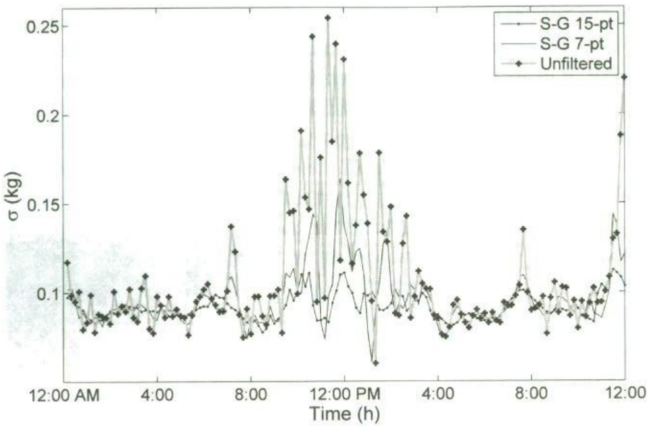

Fig. 4. Comparison of standard deviations for 24 h of unfiltered data, 7-point SG filter, and 15-point SG filter. Data were collected every 10 min on January 26, 2008.

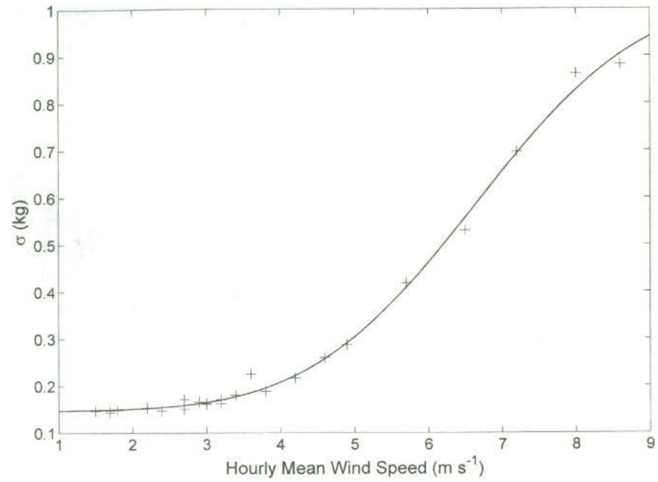

Fig. 5. Relationship of hourly wind speed and standard deviation for 2,560-point samples of lysimeter mass

addressed by averaging methods. The arithmetic mean of the data is equivalent to the direct current component of the Fourier transform so taking the mean can be regarded as low-pass filtering of all higher frequency components. The second issue concerns lower frequencies (<0.1 Hz) where noise is also a factor but separation of a vibrational component of observed mass from the actual signal may be problematic. This problem was addressed by SG methods applied to data taken at 10-min intervals.

Comparison of Mean and Median Averaging Methods

The mean and median of 256-point segments from the filter assessment data set were computed to construct a ten-element vector for each statistic. The standard deviations of the mean and median vectors were calculated for each data collection during a 24-h period. Taking the mean of these standard deviations resulted in a slightly smaller average standard deviation for the mean vectors (0.108 kg) as compared to the median (0.112). This minor improvement plus the simplicity of programming makes the arithmetic mean preferable.

Effect of Wind Loading on Lysimeters

The standard deviation of unfiltered mass data collected on January 26, 2008 was highest during the middle of the day and was substantially reduced at night (Fig. 4). Wind speed is also normally reduced at night suggesting that a correlation of standard deviations of lysimeter mass and wind speed might exist. Standard deviations were calculated for six 2,560-point samples/h taken at the crop lysimeter for a 24-h period. The mean hourly wind speed was obtained for CIMIS weather station No. 2 located approximately 200 m south of the crop lysimeter. The hourly mean of these standard deviations of lysimeter mass bears a distinct nonlinear relationship to mean hourly wind speed (Fig. 5).

It is reasonable to expect that as wind speed approaches zero other factors that could influence lysimeter vibration such as microseismic activity will become important and dependence on wind speed will vanish. Thus, the form of the dependence of standard deviation of lysimeter mass on wind speed should be approximated by a function that is relatively constant at low values but increases as wind speed increases beyond a threshold value. The error function has this behavior, so a parameterized error function was fitted to provide an approximation of the standard deviations of lysimeter mass at least in the range of wind speed of the data ($1-9\ \mathrm{m\,s^{-1}}$, Fig. 5). The fitted curve has the form $\sigma=a(1)-a(2)\mathrm{erf}[-a(3)U-a(4)]$, where U=wind speed; the coefficients $a(\cdot)$=model parameters; and erf=error function (Press et al. 1996, Sec. 6-2). For the best-fit curve the vector $a=[0.584\ 0.438\ 0.397\ 2.63]$. It is cautioned that extrapolation of the fitted function to higher wind speed is unwarranted. However, the standard deviation of mass measurements for the crop lysimeter is certainly strongly influenced by changes in wind speed above approximately $3.5\ \mathrm{m\,s^{-1}}$ (Fig. 5). This observation confirms earlier suppositions that wind affected the accuracy of lysimeter measurements (Brown et al. 2001; Howell et al. 1985; Pruitt and Angus 1960).

Comparing Effectiveness of the Filtering Methods

Averaged standard deviations calculated for three SG filters (7, 11, and 15 point) decreased as filter length increased (Table 1). For the 24-h period, increasing the length of the filter reduced noise somewhat, implying that the 15-point filter was the best choice. When only daytime data collected from 6:55 a.m. through 4:55 p.m. were considered, filtering provided greater noise reduction (Fig. 4, Table 1). Thus, filtering is more effective during the daytime when the most important ET rate data are obtained.

Table 1. Performance of Savitsky–Golay and Frequency Filtering Methods

	Standard deviation		Noise reduction[b]	
Method	24-h data set (kg)	Daytime data set[a]	24-h data set	Daytime data set
Unfiltered	0.107	0.123	—	—
SG 7 point	0.096	0.101	0.90	0.88
SG 11 point	0.094	0.095	0.88	0.85
SG 15 point	0.092	0.092	0.86	0.83

[a]Collected from 6:55 a.m. to 4:55 p.m.

[b]The dimensionless reduction factor is the ratio of standard deviation of SG filtered data to the standard deviation of mean values for ten 256-point subsequences of unfiltered data.

As the number of points in the SG filter is increased, the startup time to obtain estimates of the ET rate also increases. For example, after collection of the first point, a 15-point filter would take 140 min to generate the first smoothed data point. Filtering must be restarted every night after the on-board irrigation water tanks are refilled so some other ET estimation method would be needed during the time when the initial data required to start the filter are being collected. A similar problem exists prior to refilling the water tanks. Also, as the length of the filter increases, the quadratic approximation used in the SG filtering process would tend to smooth out rapid changes in ET rate. This effect could bias data obtained during the early morning and early evening when the magnitude of the time derivative of the ET rate is largest. For these reasons a 7-point SG filter has been included in regular data acquisition for both lysimeters.

Another method for minimizing the effects of noise involves taking data less frequently and averaging them over longer periods (Howell et al. 1995; Young et al. 1996). Lysimeter measurement of ET for bermudagrass and ryegrass in Arizona used a sampling interval of 2 s and an averaging period of 10 min (Brown et al. 2001). Latent heat flux was calculated from weighing lysimeter data taken every 6 s and averaged over 5 min (Todd et al. 2000). If noise is a factor affecting data from these lysimeters, the present study suggests that averaging many measurements taken over a period of approximately 1 min could be a better strategy for reducing noise caused by vibration at frequencies greater than 1 Hz. The reason is that sampling intervals greater than 1 s would cause aliasing of the data assuming higher frequencies are present. However, the selection of lower sampling rates and averaging over 5–10 min for these lysimeters may have been effective in reducing noise generated at frequencies less than 1 Hz. A disadvantage of longer averaging periods is the possibility of introducing bias into measurements due to nonlinear variation in ET rate during the averaging period. This problem would be more acute at times of day when ET rates change rapidly, precipitation events end, or when partial cloud cover causes rapid changes in net radiation.

Conclusions

Weighing lysimeters that incorporate a counterbalanced scale may suffer degraded precision of mass measurements due to vibration of the mechanical weighing system. For the grass lysimeter located at the University of California West Side Field Research and Extension Center, the writers found mechanical resonance of the weighing system at approximately 11 Hz. A more complicated set of resonance peaks were present for data taken at the crop lysimeter. The mechanical resonances were dominated by vibrational energy at frequencies greater than 1 Hz. This is an important fact because it implies that sampling intervals should be sufficiently small to eliminate aliasing. Noise due to the vibration was greatly reduced by calculating the arithmetic mean of lysimeter mass data collected over 1-min periods. Increased noise was also found at frequencies of 0.01–0.1 Hz. The reduction of ET data quality in this frequency range warranted efforts to improve the precision of lysimeter mass measurements by digital filtering using three SG filters of length 7, 11, and 15 operating on data taken at 10-min intervals. The relative merit of each filter was determined by calculating a noise reduction factor obtained relative to the arithmetic mean of lysimeter mass data. A daytime data set, collected at 10-min intervals on January 26, 2008, generated noise reduction factors of 0.88 (7 point), 0.85 (11 point) and 0.83 (15 point). The SG methods for lysimeter noise reduction do not require any specialized functions and could be programmed into any datalogger assuming sufficient memory and speed. Comparison of hourly mean values of the standard deviation of lysimeter mass with hourly mean wind speed indicated a nonlinear dependence confirming earlier suppositions that wind loading caused noise in counterbalanced weighing lysimeters.

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References

Allen, R. G., Jensen, M. E., Wright, J. L., and Burman, R. D. (1989). "Operational estimates of reference evapotranspiration." *Agron. J.*, 81(4), 650–662.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). "Crop evapotranspiration: Guidelines for computing crop water requirements." *Irrigation & Drainage Paper No. 56*, Food and Agricultural Organization of the United Nation, Rome, Italy.

Ayars, J. E., and Hutmacher, R. B. (1994). "Crop coefficients for irrigating cotton in the presence of groundwater." *Irrig. Sci.*, 15(1), 45–52.

Baldocchi, D. D. (2003). "Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: Past, present and future." *Global Change Biol.*, 9(4), 479–492.

Brown, P. W., Mancino, C. F., Young, M. H., Thompson, T. L., Wierenga, P. J., and Kopec, D. M. (2001). "Penman Monteith crop coefficients for use with desert turf systems." *Crop Sci.*, 41(4), 1197–1206.

Gavilán, P., and Berengena, J. (2007). "Accuracy of the Bowen ratio-energy balance method for measuring latent heat flux in a semiarid advective environment." *Irrig. Sci.*, 25(2), 127–140.

Holmes, J. W. (1984). "Measuring evapotranspiration by hydrologocial methods." *Agric. Water Manage.*, 8(1), 29–40.

Howell, T. A., McCormick, R. L., and Phene, C. J. (1985). "Design and installation of large weighing lysimeters." *Trans. ASAE*, 28(1), 106–112, and 117.

Howell, T. A., Schneider, A. D., Dusek, D. A., Marek, T. H., and Steiner, J. L. (1995). "Calibration and scale performance of Bushland weighing lysimeters." *Trans. ASAE*, 38(4), 1019–1024.

Kirkham, R. R., Rockhold, M. L., Gee, G. W., Fayer, M. J., and Campbell, M. D. (1991). "Lysimeter: Data acquisition and analysis." *Proc., Int. Symp. on Lysimeters for Evapotranspiration and Environmental Measurements*, R. Allen, T. Howell, W. Pruitt, I. Walter, and M. Jensen, eds., American Society of Agricultural Engineers, Honolulu, 362–370.

Molden, D., and Oweis, T. Y. (2007). *Water for food, water for life: A comprehensive assessment of water management in agriculture*, Earthscan, London and International Water Management Institute, Sri Lanka, Colombo, 279–310.

Monteith, J. L., and Unsworth, M. H. (1990). *Principles of environmental physics*, 2nd Ed., Edward Arnold, London.

Pereira, L. S., Perrier, A., Allen, R. G., and Alves, I. (1996). "Evapotranspiration: Review of concepts and future trends." *Evapotranspiration and Irrigation Scheduling, Proc., Int. Conf.*, ASAE, San Antonio, Tex., 109–115.

Phene, C. J., Hoffman, G. J., Howell, T. A., Clark, D. A., Mead, R. M., Johnson, R. S., and Williams, L. E. (1991). "Automated lysimeter for irrigation and drainage control." *Proc., Int. Symp. on Lysimetry*, ASCE Irrigation and Drainage Division, Honolulu, 28–36.

Phene, C. J., Meek, D. W., Davis, K. R., McCormick, R. L., and Hutmacher, R. B. (1985). "Real time crop evapotranspiration and determination of crop coefficients." *Proc., National Conf. on Advances in Evapotranspiration*, ASAE, St. Joseph, Mich., 122–129.

Press, W. H., Flannery, B. P., Teukolsky, S. A., and Vetterling, W. T. (1996). *Numerical recipes in Fortran 77: The art of scientific computing*, 2nd Ed., Cambridge University Press, Cambridge, U.K.

Pruitt, W. O., and Angus, D. E. (1960). "Large weighing lysimeter for measuring evapotranspiration." *Trans. ASAE*, 3(1), 13–15.

Pruitt, W. O., and Doorenbos, J. (1977). "Empirical calibration, a requisite for evapotranspiration formulae based on daily or longer mean climatic data?" *International Commission on Irrigation and Drainage Conf. on Evapotranspiration*.

Temesgen, B., Eching, S., Davidoff, B., and Frame, K. (2005). "Comparison of some reference evapotranspiration equations for California." *J. Irrig. Drain. Eng.*, 131(1), 73–84.

Todd, R. W., Evett, S. R., and Howell, T. A. (2000). "The Bowen ratio-energy balance method for estimating latent heat flux of irrigated alfalfa evaluated in a semi-arid, advective environment." *Agric. Forest Meteorol.*, 103(4), 335–348.

Wright, J. L. (1982). "New evapotranspiration crop coefficients." *J. Irrig. and Drain. Div.*, 108(IR1), 57–74.

Young, M. H., Wierenga, P. J., and Mancino, C. F. (1996). "Large weighing lysimeters for water use and deep percolation studies." *Soil Sci.*, 161(8), 491–501.